National Aeronautics and
Space Administration

NASA

2018 Annual Report

Earth Science Technology Office

Executive Summary

As you'll read in the pages that follow, 2018 was another full and productive year for technology development at the NASA Earth Science Technology Office (ESTO), with numerous successes advancing new technologies for Earth science as well as the competitive selection of new projects.

In fiscal year 2018 (FY18), ESTO continued to build upon its 20-year heritage of technology development and infusion. This year, 40% of active ESTO technology projects advanced at least one Technology Readiness Level, and of the 804 completed projects in the ESTO portfolio, 33% have already been infused into Earth observing missions, operations, or commercial applications. We are particularly proud to report that nearly 110 students, high school through PhD, have been directly involved in ESTO-funded projects this year. See pages 3-6 for more on programmatic metrics.

In January 2018, the National Research Council (NRC) released the second decadal survey for Earth science: *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. As was the case with the 2007 decadal survey, ESTO investments are already well underway to directly support all of the recommended measurements, and future ESTO solicitations will help further advance these goals. (See pages 7-8)

Also of note, three technology validation projects were launched on board 6-unit CubeSats to the International Space Station (ISS) in May 2018. Following their deployment from the ISS in July, these demonstration spacecraft are taking their first measurements and sending data to the ground. (See pages 15-16)

These successes demonstrate the hard work of our principal investigators and their collaborators. In October 2017, ESTO selected 12 new projects through a competitive solicitation under the Advanced Component Technologies (ACT) program, and in July, four projects were selected under an In-Space Validation of Earth Science Technologies (InVEST) solicitation. As ESTO celebrates its 20th year, we welcome this new cohort of investigators, and we look forward to the contributions they will usher forward, ensuring a bright future for Earth science.

Pamela S. Millar
Program Director

Robert A. Bauer
Deputy Program Director

ESTO
Earth Science Technology Office

Photo: On May 21st, 2018, an Orbital ATK Antares rocket launched from Wallops Island carrying 7,400 lbs. of NASA cargo to the International Space Station, including three ESTO technology validation CubeSats. To learn more, see page 15. Credit: Aubrey Gemignani, NASA

About ESTO

As the technology development function within NASA's Earth Science Division, ESTO performs strategic technology planning and manages the development of a range of advanced technologies for future science measurements and operational requirements. ESTO employs an open, flexible, science-driven strategy that relies on competition and peer review to produce the best, cutting-edge technologies for Earth science endeavors.

Our approach to Technology Development:

- **Strategy:** Engage with the Earth science community to plan investments through careful analyses of science requirements
- **Selection:** Fund technology development through competitive solicitations and partnership opportunities
- **Management:** Actively manage the progress of funded projects with the aid of subject matter experts
- **Infusion:** Encourage and facilitate the infusion of mature technologies into science measurements

The results speak for themselves: a broad portfolio of well over 800 emerging technologies – 141 of which were active at some point during FY18 – ready to enable or enhance new science measurement capabilities as well as other infusion opportunities.

observation technology

Carefully developed technologies can reduce the risk and cost of new scientific observations with extended capabilities. ESTO's strategy for observation technologies focuses on new measurement approaches that reduce the overall volume, mass, and operational complexity in observing systems.

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technology validation

Validation on airborne and spaceborne platforms is a critical step in mitigating the risk of new technologies. ESTO actively facilitates and pursues opportunities to flight-qualify various emerging technologies – instruments, components, and information systems – in relevant environments.
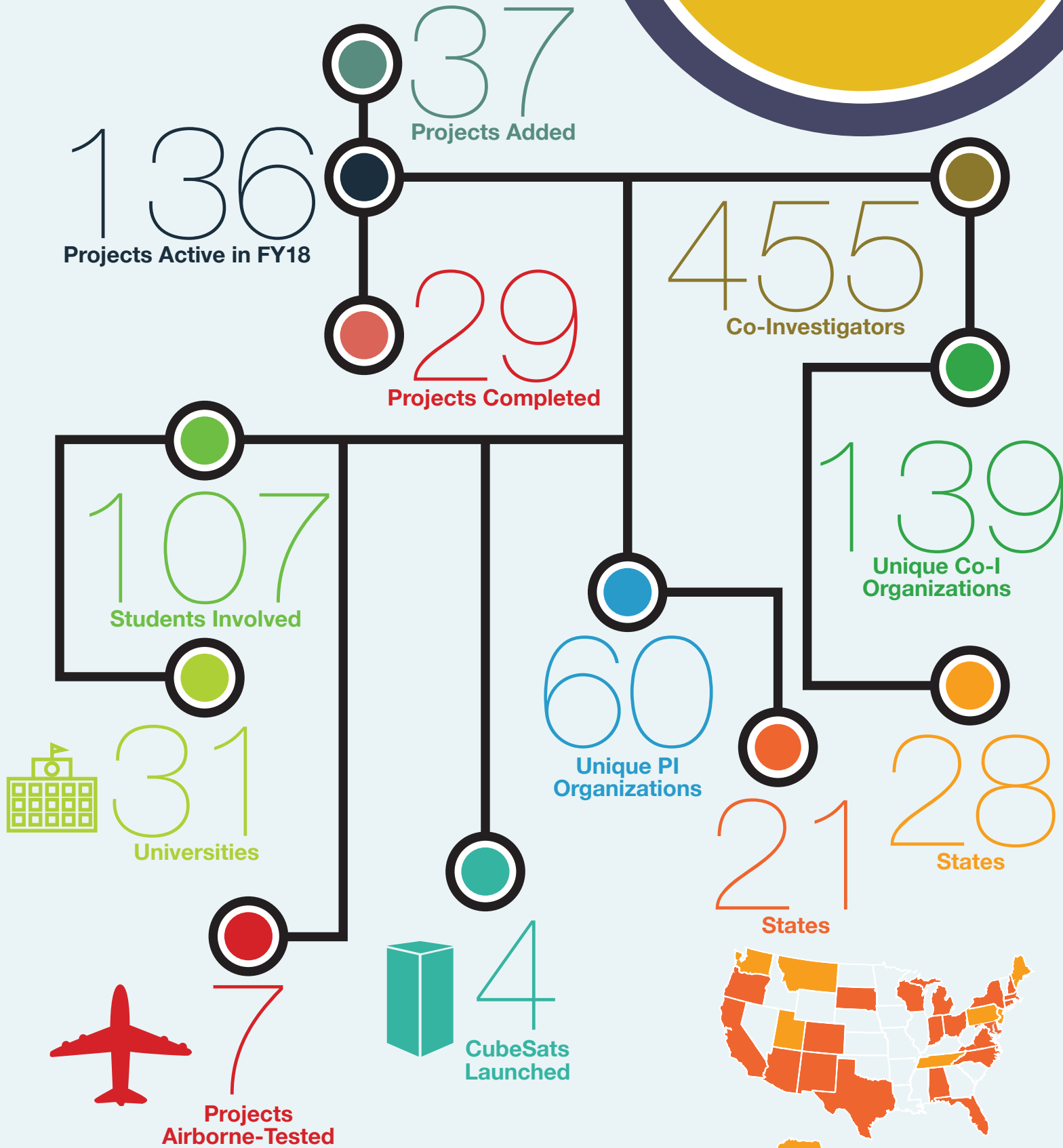
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information technology

AIST advances the mission of Earth science research by creating and refining new information system technologies. These projects increase efficiency, reduce risk, and enable new observational techniques that would be impossible without advances in information technology.

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ESTO BY THE NUMBERS

37 Projects Added

136 Projects Active in FY18

29 Projects Completed

455 Co-Investigators

139 Unique Co-I Organizations

107 Students Involved

31 Universities

60 Unique PI Organizations

21 States

28 States

7 Projects Airborne-Tested

4 CubeSats Launched

With 804 completed technology investments and a portfolio during FY18 (October 1, 2017, through September 30, 2018) of 136 active projects, ESTO drives innovation, enables future Earth science measurements, and strengthens NASA's reputation for developing and advancing leading-edge technologies. To clarify ESTO's FY18 achievements, what follows are the year's results tied to NASA's performance metrics for ESTO:

GOAL 1

Annually advance 25% of currently funded technology projects at least one Technology Readiness Level (TRL).

FY18 RESULT

25% goal
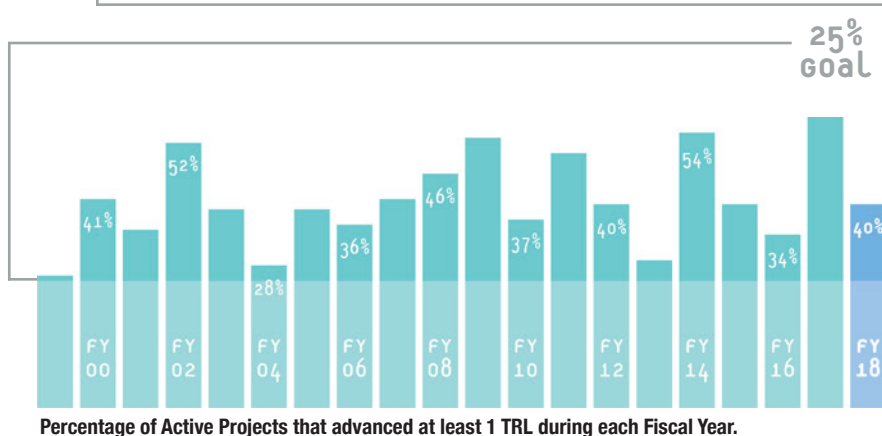
40% of ESTO technology projects funded during FY18 advanced one or more TRLs over the course of the fiscal year. 9 of these projects advanced more than one TRL. Although the percentage of TRL advancements tends to be higher in years with large numbers of completing projects, ESTO has consistently met or exceeded this metric in every fiscal year since inception. The average TRL advancement for all years going back to 1999 is 41%.

41%	52%	28%	36%	46%	37%	40%	54%	34%	40%
FY 00	FY 02	FY 04	FY 06	FY 08	FY 10	FY 12	FY 14	FY 16	FY 18

Percentage of Active Projects that advanced at least 1 TRL during each Fiscal Year.

GOAL 2

Mature at least three technologies to the point where they can be demonstrated in space or in a relevant operational environment.

FY18 RESULT

The chart to the right shows ESTO's all-time infusion success drawn from 804 completed projects through the end of FY18. In this fiscal year, at least 6 ESTO projects achieved infusion into science measurements, airborne campaigns, data systems, or follow-on development activities. Several notable examples follow.

- 33% Already Infused
- 45% Path Identified for Infusion
- 22% Awaiting Infusion Opportunity
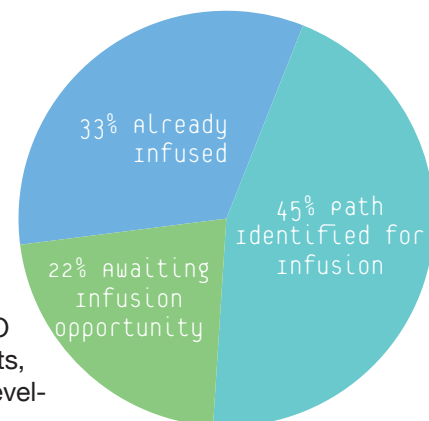
Avalanche Photodiode

The HgCdTe Infrared Avalanche Photodiode Focal Plane Array (Principal Investigator: Xiaoli Sun, Goddard Space Flight Center) is a new type of short-wave infrared to mid-wave infrared single photon detector array that features greater than 90% quantum efficiency, near-zero read-out noise, and instantaneous multi-channel outputs. Originally developed for infrared lidar and spectrometers for Earth science remote sensing, the technology has also been picked up by several other programs for use beyond Earth.

The MARs LIdar (MARLI), a NASA planetary instrument technology project currently in development, is making use of the array for potential measurements of wind and dust profiles in the Martian atmosphere. And the NASA Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) program 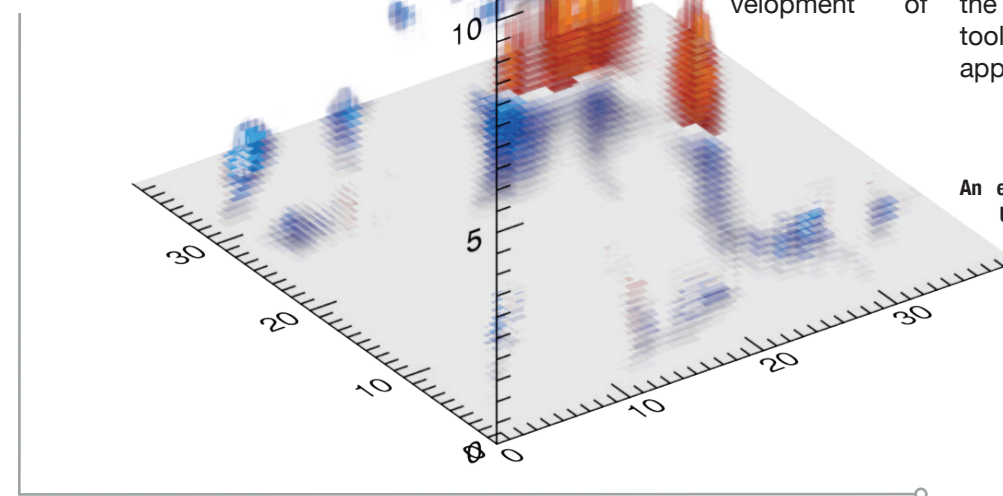has selected the array for further technology development for potential use in future planetary swath mapping laser altimeters and infrared laser absorption spectrometers.

The HgCdTe avalanche photodiode array in a mini-Stirling cryocooler. Altogether, this component weights 1.4 kg, measures 7x7x20 cm, and requires 4-7 W of power. Credit: Xiaoli Sun, GSFC

super cloud library

The Super Cloud Library (SCL), a big data analysis and visualization tool for cloud-resolving models, has been infused into the Data Analytics and Storage System (DASS) at the NASA Center for Climate Simulation (Principal Investigator: Wei-Kuo Tao, Goddard Space Flight Center). Cloud resolving models are numerical simulations of convective clouds or storms that help scientists explore cloud phenomena and aid in the development of improved weather and climate models. Using Apache Spark, an analytics engine for big data process, and Apache Hadoop, a utility that links computers together in a network for data intensive computations, the SCL has demonstrated 20x speed improvements over previous manual processes. Beyond operational use, the DASS expects to use the new tool as a benchmark to evaluate new approaches.

An example simulation showing a rain event. Updraft is shown in red and rain in blue. Credit: Wei-Kuo Tao, GSFC

earth venture suborbital

In September 2018, five proposals were selected under the 2017 Earth Venture Suborbital-3 (EVS-3) solicitation, which sought complete, suborbital, principal investigator-led investigations to conduct innovative, integrated, hypothesis or science question-driven approaches to pressing Earth system science issues. Four of these include infusions of ESTO technologies:

- The Submesoscale Ocean Dynamics and Vertical Transport experiment (S-MODE; Thomas Farrar, Woods Hole Oceanographic Institute) will study submesoscale ocean dynamics and their contributions to vertical exchange of climate and biological variables in the upper ocean. The experiment will utilize several new instruments developed under ESTO, including the Ka-band Doppler Scatterometer (DopplerScatt: Perkovic-Martin, JPL) and the Portable Remote Imaging Spectrometer (PRISM: Mouroulis, JPL) to provide an unprecedented view of submesoscale eddies and fronts and their effects on vertical transport in the upper ocean.

- Delta-X: Enabling Deltas to Thrive in a Century of Rising Seas (Marc Simard, Jet Propulsion Laboratory) will use state-of-the-art airborne remote sensing and in situ instruments to calibrate hydrology, sediment transport and plant productivity models around the Mississippi delta floodplain in order to understand potential impacts of sea-level rise. Delta-X will utilize the Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR: Hensley and Lou, JPL) for land vegetation measurements, the Airborne Surface Water and Ocean Topography (AirSWOT: Rodriguez, JPL) for water surface elevation measurements, and the Airborne Visible InfraRed Imaging Spectrometer - Next Generation (AVIRIS-NG: Green, JPL) for spectral measurements of ecosystem, geology, and soil.

- The Aerosol Cloud Meteorology Interactions Over the Western Atlantic Experiment (ACTIVATE; Armin Sorooshian, University of Arizona) will study interactions of aerosol particles and clouds, a large uncertainty in global radiative forcing estimates. ACTIVATE will use the High Spectral Resolution Lidar-2 (HSRL-2: Hostetler, LaRC) to characterize clouds and aerosols in the atmosphere.

Engineers install the DopplerScatt radar instrument on the NASA B200. Credit: Ken Ulbrich, NASA

• Using instruments carried by the high-altitude ER-2 aircraft, the Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS; Lynn McMurdie, University of Washington) will provide important observations for understanding the mechanisms of snow band formation and evolution within winter storms, as well as data for future mission design and model improvements. Among the instruments IMPACTS will utilize is the dual frequency (Ku- and Ka-band) High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP: Heymsfield, GSFC) as well as a W-band antenna developed for the W-band Cloud Radar System (Racette and Li, GSFC).

The HIWRAP dual frequency Doppler radar.
Credit: Bill Hrybyk, NASA

GOAL 3

Enable a new science measurement or significantly improve the performance of an existing technique.

FY18 RESULT
### A New Approach to Soil Moisture Measurements

Global root zone soil moisture (or RZSM) measurements – water content in the top meter of soil – are a missing data set that can provide a critical link between surface hydrology and deeper processes. They could directly aid our understanding of drainage characteristics, water uptake by plants, food production, and the connection between precipitation and fresh water availability, a factor that is presently available only through model assimilation of surface soil moisture.

Various remote sensing concepts to measure RZSM have focused on spaceborne L-band radars, which require very large (12-30 meter) antennas to meet resolution requirements and can suffer from interference from other sources. The Signals of Opportunity Airborne Demonstration (SoOp-AD) project has developed a new passive P- and S-Band microwave instrument to directly measure root zone soil moisture (RZSM) at depths of 0 to 30 cm using reflected "signals of opportunity" – signals that are already being generated by satellite commu-

nications. The result is a substantially smaller antenna and orders of magnitude lower power requirements than traditional active radar, which requires a signal transmitter.

The SoOp-AD instrument was designed and developed by James Garrison at Purdue University and includes a P/S-band (240 – 270 GHz) receiver system made up of a dual linear polarization antenna, and two 4-channel digital receivers. In late 2016, the project team took the instrument on several flights on board a NASA B-200 aircraft over instrumented field sites near the Little Washita watershed, Oklahoma. Further field experiments were conducted at the Purdue Agronomy Center for Research and Education to characterize reflected signals and demonstrate soil moisture retrievals under controlled conditions.

The experiments have proved SoOp-AD a viable, and novel, approach for next-generation soil measurements from space. The project team has been awarded a 2017 In-Space Validation of Earth Science Technologies (InVEST) grant to further demonstrate the concept on a CubeSat platform (see page 14 for the 2017 InVEST awards).
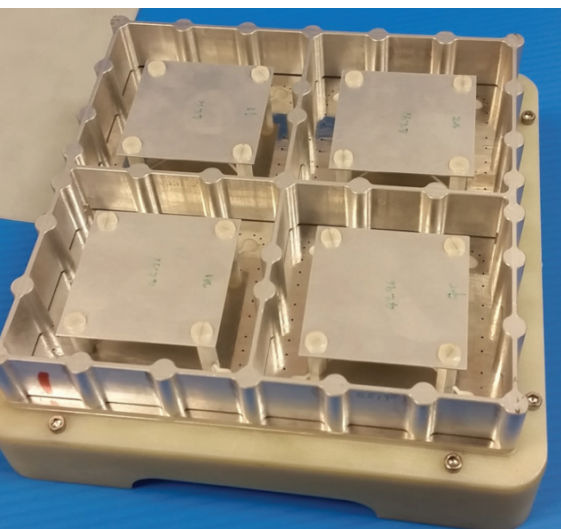
2x2 element S-Band array from the SoOp-AD project.
Credit: James Garrison, Purdue University

As with many research and development projects, students are integral to the work and success of technology development teams. Since ESTO's founding, more than 825 students from over 143 institutions have worked on various ESTO-funded projects. Aided by their experiences, these students have often gone on to work in the aerospace industry and in related fields.

In FY18, 107 students were involved with active ESTO projects. Most typically, these students are pursuing undergraduate and graduate degrees, but occasionally high school students also join in on the technology development work.

STUDENT PARTICIPATION

student spotlight:
Rachel Norris

Rachel Norris, a Ph.D. student in Electrical and Computer Engineering at the University of Michigan and 2018 NASA Earth and Space Science Fellowship (NESSF) recipient, is working on the Next-Generation Global Navigation Satellite System (GNSS) Bistatic Radar Receiver (or NGRx) project with principal investigator Chris Ruf. NGRx is a dual-band instrument under development capable of measuring ocean surface wind speed in the core of tropical cyclones as well as soil moisture, inland flooding extent, and ice thickness with relatively high spatio-temporal resolution. It could serve as a follow-on to the NASA Cyclone Global Navigation Satellite System (CYGNSS) mission. Ms. Norris has a life-long interest in severe weather and holds B.S. degrees in Electrical Engineering and Meteorology from the University of Oklahoma. For NGRx, she is contributing to the radio frequency hardware development and instrument front-end testing, and plans to play a significant role in upcoming ground and airborne tests.
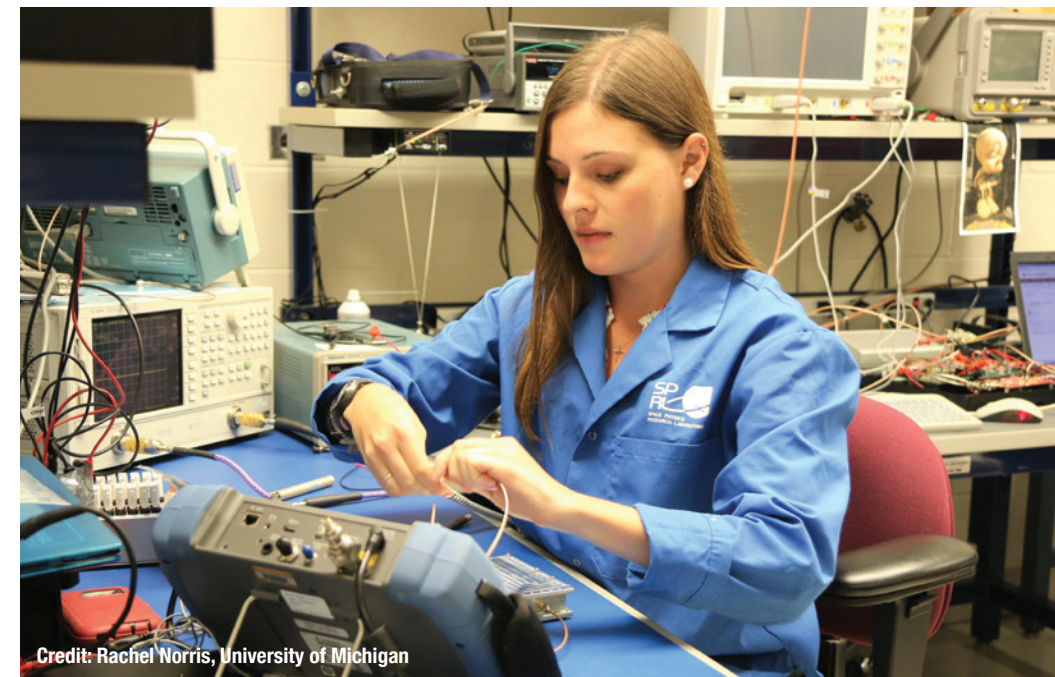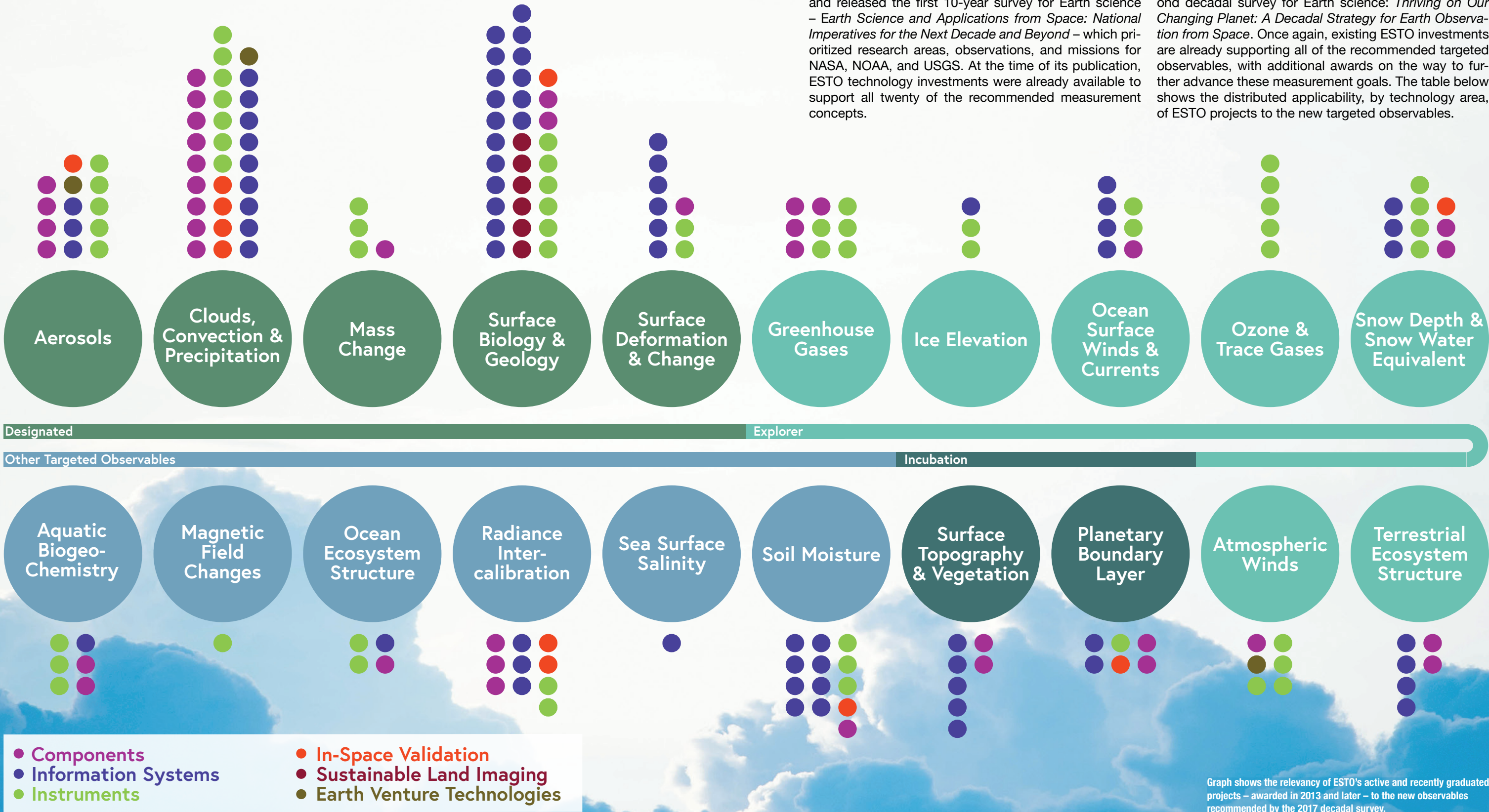
Credit: Rachel Norris, University of Michigan

LEADING IN A NEW DECADE

In 2007, the National Research Council (NRC) completed and released the first 10-year survey for Earth science – E*arth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* – which prioritized research areas, observations, and missions for NASA, NOAA, and USGS. At the time of its publication, ESTO technology investments were already available to support all twenty of the recommended measurement concepts.

Ten years on, in January 2018, the NRC released a second decadal survey for Earth science: *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. Once again, existing ESTO investments are already supporting all of the recommended targeted observables, with additional awards on the way to further advance these measurement goals. The table below shows the distributed applicability, by technology area, of ESTO projects to the new targeted observables.

Designated | Explorer

Other Targeted Observables | Incubation

Aerosols · Clouds, Convection & Precipitation · Mass Change · Surface Biology & Geology · Surface Deformation & Change · Greenhouse Gases · Ice Elevation · Ocean Surface Winds & Currents · Ozone & Trace Gases · Snow Depth & Snow Water Equivalent

Aquatic Biogeo-Chemistry · Magnetic Field Changes · Ocean Ecosystem Structure · Radiance Inter-calibration · Sea Surface Salinity · Soil Moisture · Surface Topography & Vegetation · Planetary Boundary Layer · Atmospheric Winds · Terrestrial Ecosystem Structure

- ● Components
- ● Information Systems
- ● Instruments
- ● In-Space Validation
- ● Sustainable Land Imaging
- ● Earth Venture Technologies

Graph shows the relevancy of ESTO's active and recently graduated projects – awarded in 2013 and later – to the new observables recommended by the 2017 decadal survey.

observation tech

Carefully developed instrument and component technologies can reduce the risk and cost of new scientific observations with extended capabilities. ESTO's strategy for observation technologies focuses on new measurement approaches that can enable improved science capabilities and technologies to reduce the overall volume, mass, and operational complexity in observing systems. Developing and validating novel observation technologies before mission development improves their acceptance and infusion by mission planners and significantly reduces cost and schedule uncertainties. ESTO's Observation Technology investments are divided among three main programs: the Instrument Incubator Program (IIP), Advanced Component Technologies (ACT), and Sustainable Land Imaging-Technology (SLI-T).

The IIP program held 42 investments in FY18. Seven projects graduated over the course of the year, all advancing at least one Technology Readiness Level:

- *High Accuracy Vector Helium Magnetometer (HAVHM)* – Andy Brown, Polatomic Inc.
- *TIRCIS: A Thermal Infrared, Compact Imaging Spectrometer for Small Satellite Applications* – Robert Wright, University of Hawaii at Manoa
- *UWBRAD: Ultra Wideband Software Defined Microwave Radiometer for Ice Sheet Subsurface Temperature Sensing* – Joel Johnson, The Ohio State University
- *Wide-swath Shared Aperture Cloud Radar (WiSCR)* – Lihua Li, NASA Goddard Space Flight Center (GSFC)
- *HSRL for Aerosols, Winds, and Clouds using Optical Autocovariance Wind Lidar (HAWC-OAWL)* – Sara Tucker, Ball Aerospace & Technologies Corp
- *Cold Atom Gravity Gradiometer for Geodesy* – Babak Saif, NASA GSFC
- *Signals of Opportunity Airborne Demonstrator (SoOp-AD)* – James Garrison, Purdue University

observation tech: IIP

The Instrument Incubator Program (IIP) provides funding for new instrument and observation techniques, from concept to breadboard and flight demonstrations. Instrument technology development of this scale, outside of a flight project, consistently leads to smaller, less resource-intensive instruments that reduce the costs and risks of mission instrumentation.
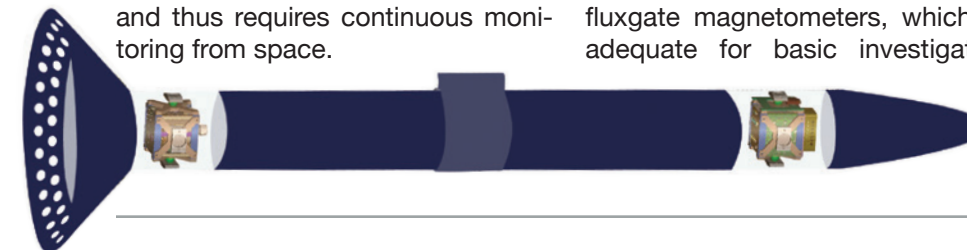
PROJECT SPOTLIGHT: testing an improved magnetometer

The internal structure of the Earth still holds many scientific mysteries, and greater insight into deep Earth phenomena could aid our understanding of plate tectonics, seismic activity, and even subtle variations in the earth's rotation. Because of their inaccessibility, subsurface features can only be studied indirectly, such as through measurements of Earth's magnetic field. This property, which also provides a layer of protection from space radiation, changes on sub-annual to decadal time scales and thus requires continuous monitoring from space.

**ABOVE: A view from the DC-3. Credit: Andy Brown
BELOW: A schematic of the CubeSat-sized sensors and electronics packages in a tow body.
Credit: Mike Clarke**

The current approach to studying magnetic fields from space employs fluxgate magnetometers, which are adequate for basic investigations of magnetic fields. However, the current technology can experience instabilities that introduce significant, random errors into the measurements. A new technology developed by Andy Brown at Polatomic, Inc. is set to provide the required sensitivity in a CubeSat form factor that could one day enable a constellation of magnetometers as called for in the 2017 Decadal Survey.

The High Accuracy Vector Helium Magnetometer (HAVHM) is an IIP-13 project that finished with an airborne flight test in October 2017. Two tow bodies containing CubeSat-sized magnetometers were dragged behind a DC-3 aircraft to avoid magnetic contamination from the aircraft. After 5.5 hours of flying over rural Texas, HAVHM was found to perform successfully, and the technology advanced to a final TRL of 6.

PROJECT SPOTLIGHT: toward a cubesat INSAR

In early July while the Kilauea eruption continued its slow-motion consumption of houses on Hawaii's big island, a Cessna 208 flew over the rift zone with a new technology which aims to help researchers predict explosive eruptions and other seismic activity in the future.

The CubeSat Imaging Radar for Earth Science-Instrument Development and Detection (CIRES-IDD) project led by Lauren Wye at SRI International utilizes interferometric synthetic aperture radar (InSAR) to detect millimeter-scale deformations in the earth's crust. InSAR works by comparing the phase differences in radar images over time, and faster revisit times would greatly enhance understanding of how certain natural hazards unfold.

Wye's team has worked to miniaturize InSAR technology to the CubeSat form factor which would allow constellations of InSAR CubeSats to monitor deformation events on much shorter time scales. Their flights over Kilauea were the first science collection campaign for their instrument and represent a crucial stepping stone on their trek towards low earth orbit.

A view of Kilauea Volcano taken from the Cessna 208 during test flights. Credit: Lauren Wye, SRI International

Advanced Component Technologies (ACT) implements technology developments to advance state-of-the-art instruments, Earth- and space-based platforms, and information systems. The ACT program funds the research, development, and demonstration of component- and subsystem-level technologies to reduce the risk, cost, size, mass, and development time of missions and infrastructure.

Project spotlight: New Radiometers to be Demonstrated in space

Continuous, precise measurements of the Sun's radiant energy – usually expressed as the Total Solar Irradiance (TSI) and by wavelength as the Spectral Solar Irradiance (SSI) – are critical to our understanding of solar variability and the climate here on Earth. Using carbon nanotube and micro-machining techniques, the Carbon Absolute Electrical Substitution Radiometers (CAESR) project at the Laboratory for Atmospheric and Space Physics at the University of Colorado has designed and developed two electrical substitution radiometers jointly with the National Institute of Standards and Technology in Boulder. These ambient temperature radiometers have nano-watt to pico-watt noise levels and do not require active cooling. The highly-integrated design enables TSI/SSI measurements that are more precise and at much lower cost. Both radiometers have upcoming demonstrations in space on board 6U CubeSats.

The first radiometer, for SSI measurements, has a 130 pico-watt noise floor and has excellent performance across the broad solar spectrum from extreme ultraviolet to mid infrared. The Compact Spectral Irradiance Monitor (CSIM) validation project will utilize this radiometer to demonstrate performance against existing NASA missions: the Solar Radiation and Climate Experiment (SORCE) and the Total and Spectral Solar Irradiance Sensor (TSIS). CSIM is expected to launch in late 2018.

The second, for TSI measurements, is high power, accurate (0.01% radiometric accuracy), and stable across the entire integrated solar spectrum. It forms the basis for the Compact Total Irradiance Monitor (CTIM) validation project, selected in July 2018 through the InVEST program (see page 14). CTIM will demonstrate TSI measurements from a CubeSat platform for the first time, potentially reducing the risk of data gaps for a measurement that has been made from space continuously for 40 years.

The ACT Program included 26 projects in FY18, 12 of which were added in October 2017 through a competitive solicitation. These new awards are as follows:
- *Geodetic Reference Instrument Transponder for Small Satellites (GRITSS)* – Christopher Beaudoin, University of Massachusetts, Lowell
- *Metamaterial-Based, Low SWaP, Robust and High Performance Hyperspectral Sensor for Land and Atmospheric Remote Sensing* – Igor Bendoym, Phoebus Optoelectronics
- *Planar Metasurface Reconfigurable W-Band Antenna for Beam Steering* – Nacer Chahat, Jet Propulsion Lab (JPL)
- *Integrated Receiver and Switch Technology (IRaST)* – William Deal, Northrop Grumman Systems Corporation
- *Laser Transmitter for Space-Based Water Vapor Lidar* – Tso Yee Fan, MIT/Lincoln Laboratory
- *P/I Band Multi-Frequency Reflectometry Antenna for a U-Class Constellation* – James Garrison, Purdue University
- *Very Long Wavelength Infrared Focal Plane Arrays for Earth Science Applications* – Sarath Gunapala, JPL
- *IMPRESS Lidar: Integrated Micro-Photonics for Remote Earth Science Sensing Lidar* – Jonathan Klamkin, University of California, Santa Barbara
- *Computational Reconfigurable Imaging Spectrometer (CRISP)* – Adam Milstein, MIT/Lincoln Laboratory
- *Correlator Array-Fed Microwave Radiometer Component Technologies* – Jeffrey Piepmeier, NASA GSFC
- *Advanced Photon-Counting Detector Subsystem for Spaceborne Lidar Applications* – John Smith, NASA Langley Research Center
- *A Black Array of Broadband Absolute Radiometers (BABAR) for Spectral Measurements of the Earth* – Michelle Stephens, National Institute of Standards & Technology

Five projects also graduated from ACT funding in FY18, all of which advanced at least one Technology Readiness Level:
- *A G-Band Humidity Sounding Radar Transceiver* – Ken Cooper, JPL
- *Ka Band Highly Constrained Deployable Antenna for RainCube* – Yahya Rahmat-Samii, University of California, Los Angeles
- *Compact Magnet-less Circulators for ACE and Other NASA Missions* – Anton Geiler, Metamagnetics, Inc.
- *Wideband Radio Frequency Interference Detection for Microwave* – Priscilla Mohammed, Morgan State University
- *Lidar Orbital Angular Momentum Sensor (LOAMS)* – Carl Weimer, Ball Aerospace & Technologies Corporation
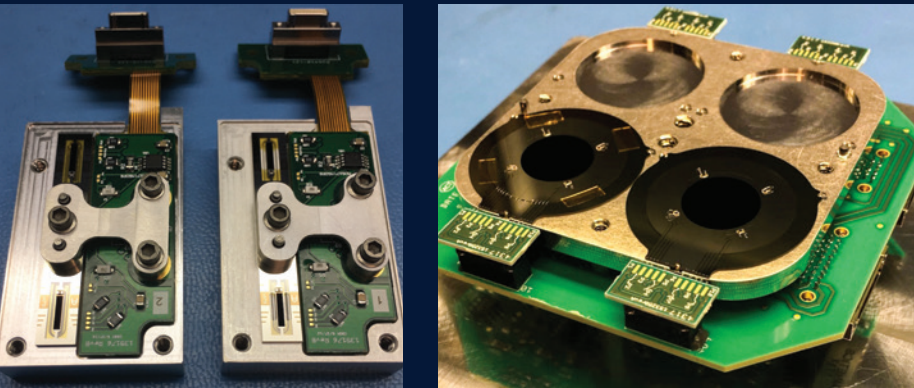
LEFT: Flight SSI/CSIM radiometers. RIGHT: Prototype TSI/CTIM detector head. Credit: David Harber

For over 40 years, the Landsat series of satellites has been providing a continuous stream of moderate resolution, multispectral images that have been used by a broad range of specialists to analyze our world. To continue the mission of Landsat, NASA initiated the **Sustainable Land Imaging – Technology (SLI-T)** program to explore innovative technologies to achieve Landsat-like data with more efficient instruments, sensors, components and methodologies. Through SLI-T, ESTO currently manages six projects focused on science enhancement and reductions in instrument volume, mass, and power usage.

PROJECT SPOTLIGHT: Compact Multispectral Imaging

The Reduced Envelope Multispectral Imager (REMI) project at Ball Aerospace is developing a conceptual multispectral imager for the Landsat 10 mission that could be up to 30-times smaller, 10-times lighter, and use 6-times less power than the Operational Land Imager (OLI) currently on board the Landsat 8 satellite. REMI achieves these reductions using a precision, two-axis mechanism to stabilize the scene during step-scan image acquisition, as opposed to the whisk broom or push broom scan methods of prior Landsat missions. The REMI architecture also features a single, reflective aperture that can also support thermal infrared channels, and a vastly simplified, and lower risk, focal plane compared to OLI. Airborne engineering tests are planned in late 2018 on board a Twin Otter aircraft, followed by science test flights in 2019.

BELOW: A close-up view of the REMI scan mirror during optical alignment. Credit: Dennis Nicks
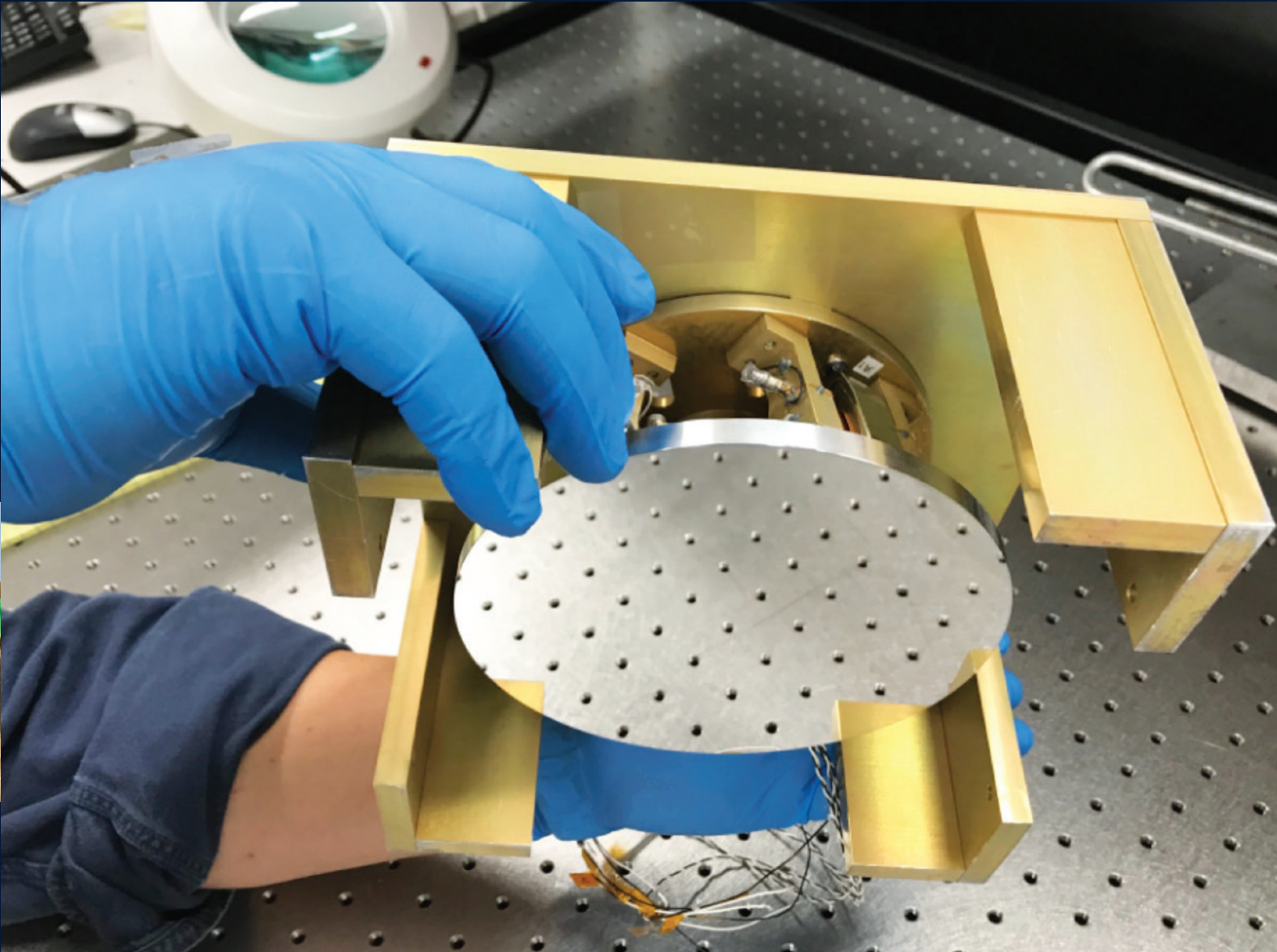
technology validation

NASA's vision for future Earth observations necessitates the development of emerging technologies capable of making new or improved Earth science measurements. Promising new capabilities, however, bring complexity and risk, and for some technologies there remains a critical need for validation in the hazardous environment of space. ESTO's In-Space Validation of Earth Science Technologies (InVEST) program facilitates the space demonstration of technology projects that cannot be sufficiently evaluated on the ground or through airborne testing. Once validated in space, technologies are generally more adoptable, even beyond their intended use.

The InVEST program held 13 projects in FY18, four of which were added in July through a competitive solicitation:

- *SNOOPI: SigNals-Of-Opportunity P-band Investigation* – James Garrison, Purdue University
- *Hyperspectral Thermal Imager (HyTI)* – Robert Wright, University of Hawaii, Honolulu
- *Compact Total Irradiance Monitor Flight Demonstration* – David Harber, University Of Colorado Boulder
- *Compact High-Resolution Trace-Gas Hyperspectral Imagers, with Agile On-board Processing* – Steven Love, Los Alamos National Security

Four other InVEST projects ended over the course of the fiscal year:

- *Advancing Climate Observation: Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN)* – William Swartz, Johns Hopkins University, Applied Physics Laboratory
- *IceCube: Spaceflight Validation of an 883-GHz Submillimeter Wave Radiometer for Cloud Ice Remote Sensing* – Dong Wu, NASA GSFC
- *The Microwave Radiometer Technology Acceleration (MiRaTA) CubeSat* – Kerri Cahoy, MIT Space Systems Lab
- *CubeSat Infrared Atmospheric Sounder (CIRAS)* – Thomas Pagano, JPL

FOUR NEW PROJECTS AWARDED UNDER THE INVEST PROGRAM
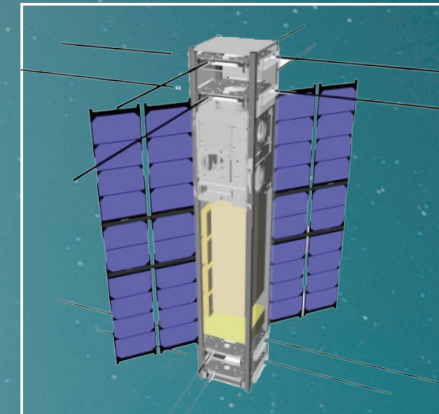
SigNals-of-Opportunity P-band Investigation (SNoOPI)
PI: James Garrison, Purdue University
SNoOPI aims to be the first demonstration of the P-band "signals of opportunity" technique from orbit to estimate the important hydrologic variables of root zone soil moisture and snow water equivalent, circumventing many current limitations under all weather conditions day and night. This technique has great promise for making measurements in previously inaccessible frequencies. *Technology Heritage: SoOp-AD Instrument, IIP*

Compact Total Irradiance Monitor (CTIM)
PI: David Harber, University of Colorado Boulder
CTIM will apply recently-proven fabrication techniques using carbon-nanotube radiometers to build a Total Solar Irradiance (TSI)-measuring instrument providing the net radiant input for climate and radiation balance studies. This compact, lower-mass instrument has shorter fabrication times and lower costs which could reduce the risk of future TSI-measurement data gaps. *Technology Heritage: CAESR Radiometers, ACT; CTIM, IIP*
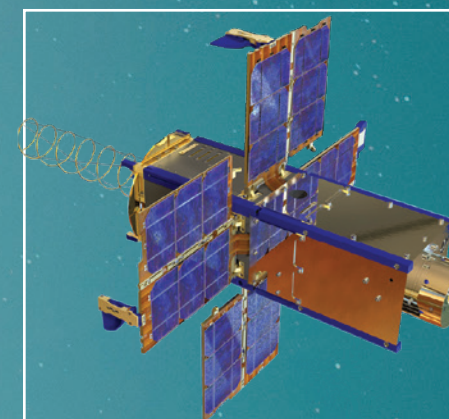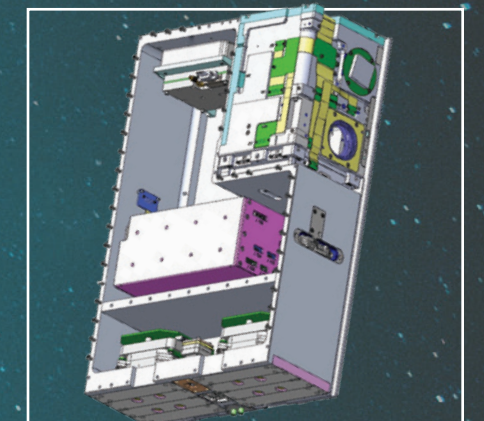
Compact High-Resolution Trace-Gas Hyperspectral Imagers
PI: Steven Love, Los Alamos National Security, LLC
This 3U CubeSat will provide an ultra-compact hyperspectral imager capable of targeting NO_2, SO_2, ozone, formaldehyde, and other gases with sufficient spectral resolution to confidently separate the trace gas signatures from the atmosphere. Operating in the 300-500nm spectral region, this instrument aims to be competitive in terms of throughput and resolution with larger satellites.

Hyperspectral Thermal Imager (HyTI)
PI: Robert Wright, University of Hawaii, Honolulu
The 6U HyTI plans to provide hyperspectral imaging in the thermal infrared bands with a spatial resolution not yet achieved from space. Using a combination of advanced signal processing and sensor fusion algorithms, not only will HyTI be able to derive very accurate land surface temperature values for a wide range of land surfaces but, and for the first time, these data and information products will be "actionable" at the individual farm level. *Technology Heritage: TIRCIS Instrument, IIP*
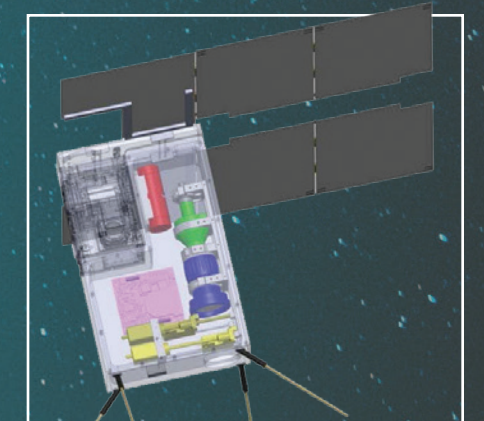
Three Cubesats Launched in 2018 are starting Technology validation operations

On May 21, three InVEST CubeSats were launched to the International Space Station (ISS) on board the Cygnus OA-9 resupply mission. Over the next few months, and following their deployment from the ISS on July 13, the 6-unit CubeSats began taking their first measurements and sending data to the ground.

RainCube

Developed at the Jet Propulsion Laboratory (JPL), RainCube will demonstrate a new architecture for miniaturized Ka-band precipitation radars. On August 27, the RainCube radar was turned on and successfully acquired the vertical range profiling measurements of precipitation and land surface at a nadir-pointing configuration. Since then, it has continued to acquire additional measurements, including this vertical precipitation profile of an over-ocean weather system off the south coast of Mexico and Guatemala on September 14. This profile features (A) stratiform precipitation under an anvil cloud; (B) a partial view of a deep convective tower; and, (C) convection and stratiform precipitation under an anvil cloud.
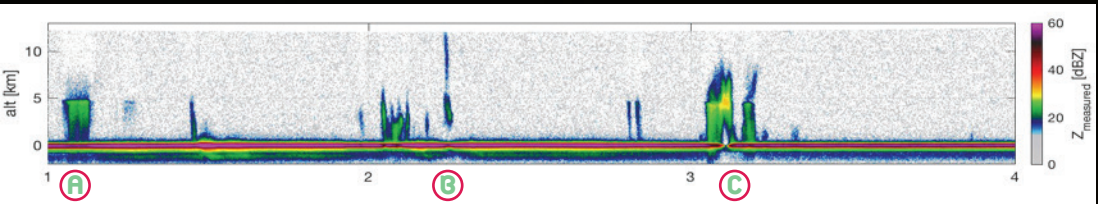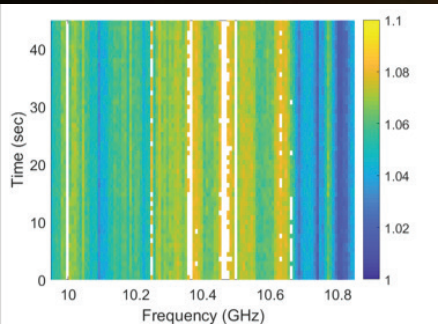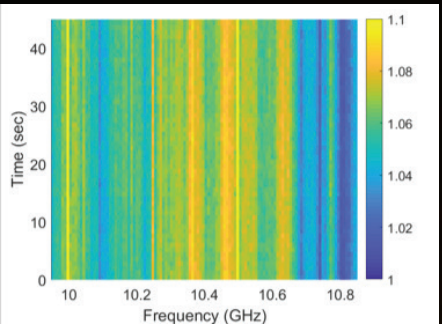

TEMPEST-D

The Temporal Experiment for Storms and Tropical Systems Demonstration (TEMPEST-D) CubeSat, led by Colorado State University with support from JPL, is testing a new five-frequency, millimeter-wave (89, 165, 176, 180 and 182 GHz) radiometer for observations of the time evolution of clouds and precipitation processes. TEMPEST-D took its first data at the beginning of September, including of Hurricane Norman off the coast of Hawaii on September 5. Shortly after becoming fully operational, TEMPEST-D captured this first full swath image of Hurricane Florence on September 11. The colors reveal the eye of the storm, surrounded by towering, intense rain bands.
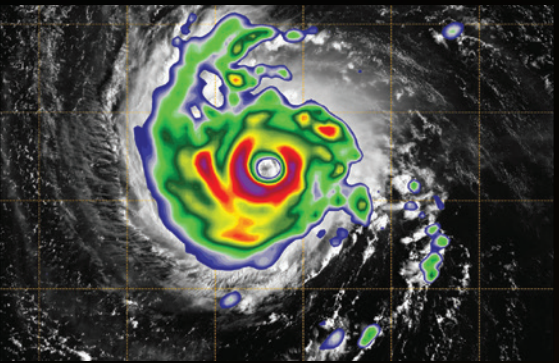

CubeRRT

The CubeSat Radiometer Radio Frequency Interference Technology (CubeRRT), developed at The Ohio State University, will validate real-time radio frequency interference (RFI) detection and mitigation technologies for future microwave radiometers. CubeRRT deployed its antenna on September 4, and is demonstrating the ability to detect RFI and filter out RFI-corrupted data in real time on board the spacecraft. Shown here are 128-frequency spectrum data collected over the Pacific Ocean on September 9, before (Left) and after (right) onboard RFI detection, flagging, and removal.

White areas mark RFI removal from the data.

RainCube and TEMPEST-D take concurrent Data of Typhoon Trami

On September 28, RainCube and TEMPEST-D overflew Typhoon Trami shortly after it had weakened to a Category 2 storm off the southern coast of Japan. Separated in time by less than five minutes, the RainCube nadir Ka-band reflectivity (vertical peaks) is shown overlaid with four levels of resolution provided by TEMPEST-D's sounding channels (horizontal layers), illustrating the complementary nature of these sensors for observing precipitation.
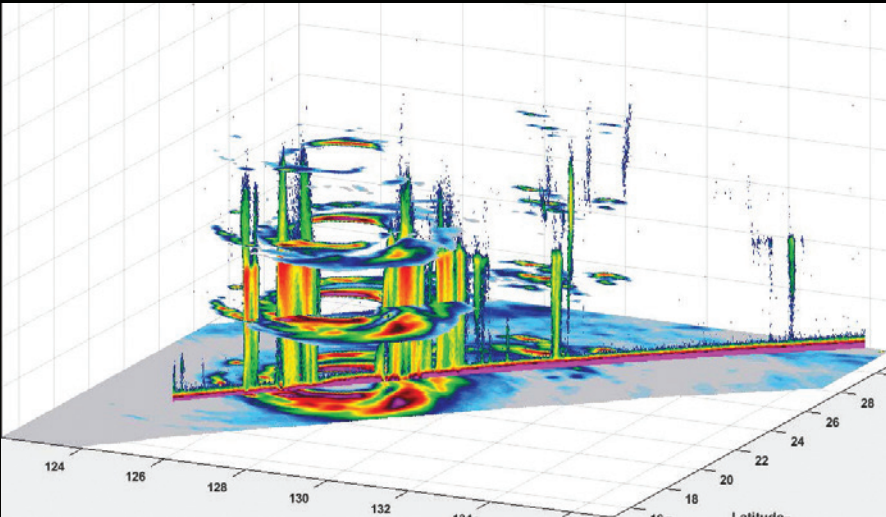
The Orbital ATK Antares rocket launch on May 21st, 2018. Credit: Aubrey Gemignani, NASA

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Information Tech

Advanced information systems play a critical role in the collection, handling, and management of the vast amounts of Earth science data, both in space and on the ground. Advanced computational systems and technology concepts that enable the capture, transmission, and dissemination of terabytes of data are essential to NASA's vision of a distributed observational network. ESTO's Advanced Information Systems Technology (AIST) program employs an end-to-end approach to develop these critical technologies — from the space segment where the information pipeline begins, to the end user where knowledge is advanced.

The AIST program held 40 active projects in FY18. Five projects graduated from funding during FY18, all of which advanced at least one Technology Readiness Level:
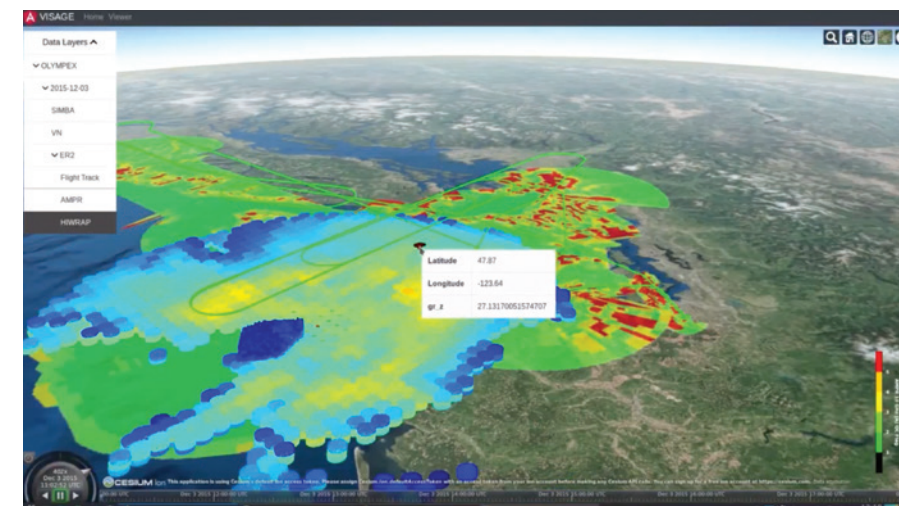
- *AMIGHO: Automated Metadata Ingest for GNSS Hydrology within OODT* – Kristine Larson, University of Colorado Boulder
- *NASA Information And Data System (NAIADS) for Earth Science Data Fusion and Analytics* – Constantine Lukashin, NASA Langely Research Center
- *Multi-Channel Combining for Airborne Flight Research using Standard Protocols* – Joe Ishac, NASA Glenn Research Center
- *Development of Computational Infrastructure to Support Hyper-Resolution Large-Ensemble Hydrology Simulations from Local-to-Continental Scales* – Martyn Clark, National Center for Atmospheric Research
- *Arctic Demonstration for SoilSCAPE (Soil moisture Sensing Controller and oPtimal Estimator)* – Mahta Moghaddam, University of Southern California

PROJECT SPOTLIGHT: Harmonizing Precipitation Data Sets

Global Precipitation Measurement (GPM) is an international satellite mission launched in 2014 to measure precipitation from space. Data from its two primary instruments are regularly compared to, and validated against, data from other satellites, as well as the GPM ground validation (GPM-GV) program which features a wide variety of ground-based, airborne, and satellite assets. These varied instruments create measurements that are likewise diverse in their formats, spatial and temporal scales, and other variables. This results in datasets that can be difficult to use together.

Visualization of AMPR data with overlay of corresponding ER-2 flight path. Credit: Helen Conover

The Visualization for Integrated Satellite, Airborne and Ground-based data Exploration (VISAGE) project is bringing together these disparate data sources into a common framework with the goal of facilitating efficient research. Using web-based interfaces, VISAGE aims to enable rapid collection and integration of data so that scientists can make qualitative and quantitative analyses and select events or features of interest (such as weather events) in near real time.

Now in their second and final year, the VISAGE team led by Helen Conover at the University of Alabama is integrating system components into a cloud environment – data readers, metadata catalog, SQL query function, on-the-fly tile generation, etc. They hope to complete testing of the full system in late 2019, and integrate it into the Global Hydrology Resource Center (GHRC) Distributed Active Archive Center (DAAC) at NASA's Marshall Space Flight Center.

PROJECT SPOTLIGHT: Tracking Global Biodiversity

Scientists' ability to track biodiversity is an important tool for monitoring ecosystem health, understanding species life cycles, and even predicting natural disasters. Until recently, however, several challenges have prevented the achievement of a holistic monitoring system. Differences in data-types, including GPS tracks, sensor-based inventories, citizen science observations, the breadth of data available, and measurement scale disparities all add complexity to the data fusion required to provide a more complete picture.

Walter Jetz at Yale University is spearheading a project to change this. His team is working to create open-source software work flows capable of fusing large biodiversity data sets. Thus far, they have successfully synced three major biodiversity catalogs and established direct access to the Google Earth Engine raster catalog. An early prototype user interface is currently being tested with nearly one billion records to visualize species' climatic niches.

This tool, in conjunction with new low-cost animal tracking systems, will allow for a dramatic improvement in the ability to study animal movements and migration and to track biodiversity changes on a global scale.

A bird outfitted with a solar-powered backpack transmitter. Credit: Max Planck-Yale Center for Biodiversity and Global Change

Future Directions

For nearly 20 years, ESTO investments have reflected and anticipated science requirements to enable many new measurements and capabilities. That ESTO technologies were already underway to address the priorities outlined by the 2017 National Academies' *Decadal Survey for Earth Science and Applications from Space* is a testament to ESTO's broad-based, inclusive strategic planning. It is the result of a commitment to monitor emerging technologies and match them to evolving needs through engagement with the science community.

Here are just a few of the emerging technology areas that could have dramatic impacts on the future of Earth science:

Integrated Micro-Photonics

Unlike electronic integrated circuits, photonic Integrated Circuits (PICs) use light rather than electrons to perform a wide variety of optical functions and can dramatically reduce the cost, size, weight, and power of remote sensing instruments while potentially improving performance and reliability. PICs could enable more frequent, lower cost missions using small satellite platforms.

Machine Learning

Artificial intelligence systems that can learn from data, identify patterns, and make decisions with little or no human intervention are already helping to sift through the terabytes of data produced by Earth science instruments. Machine learning will be a crucial tool for the complex Earth-observing scenarios envisioned for the future.
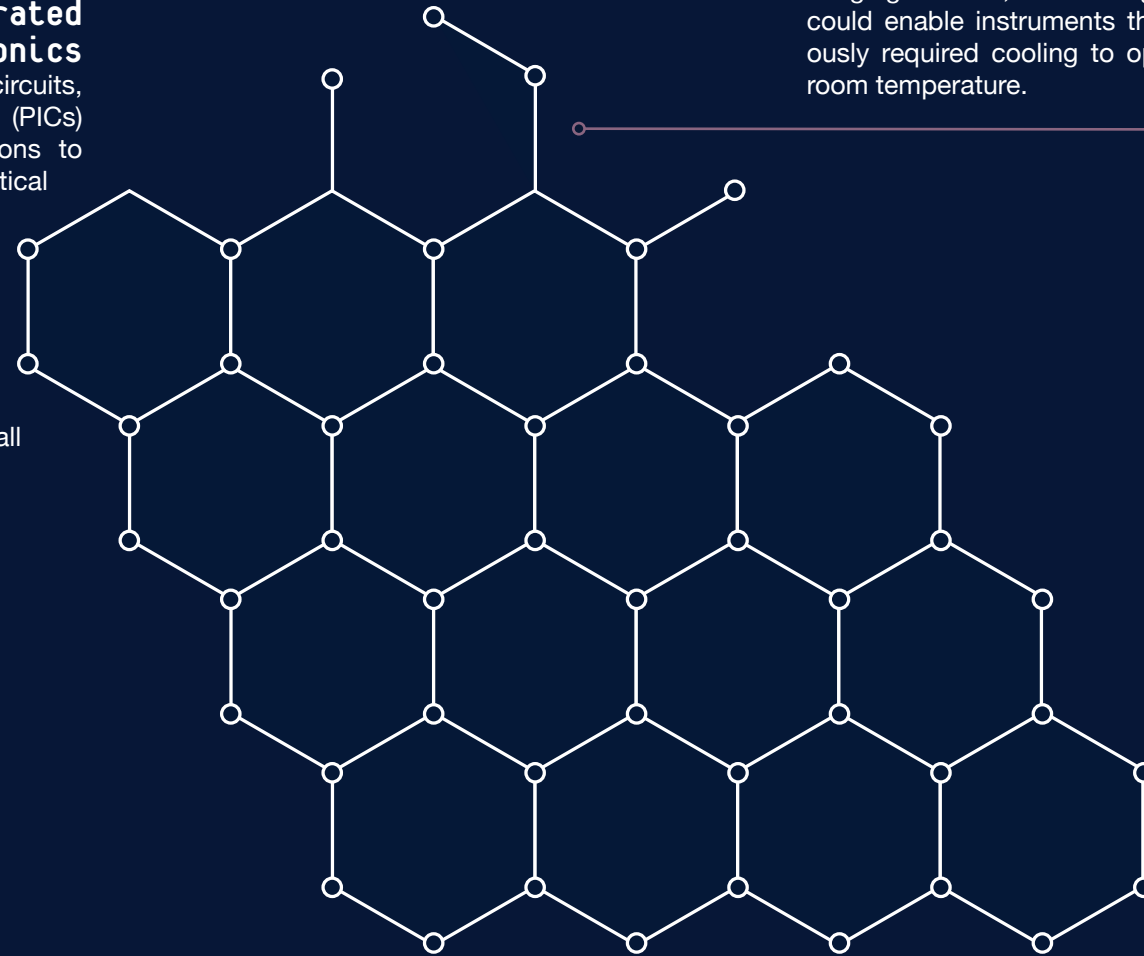
Graphene Detectors

Light, strong, and electrically and thermally conductive, graphene is poised to make an impact on infrared imaging. Of note, the use of graphene could enable instruments that previously required cooling to operate at room temperature.

High Volume Data Analytics

Large volumes of data from multiple platforms and different vantage points requires a new approach to data intercalibration and uncertainty quantification. ESTO is pursuing modernized, rapid processing workflows that can produce products within hours of observations.
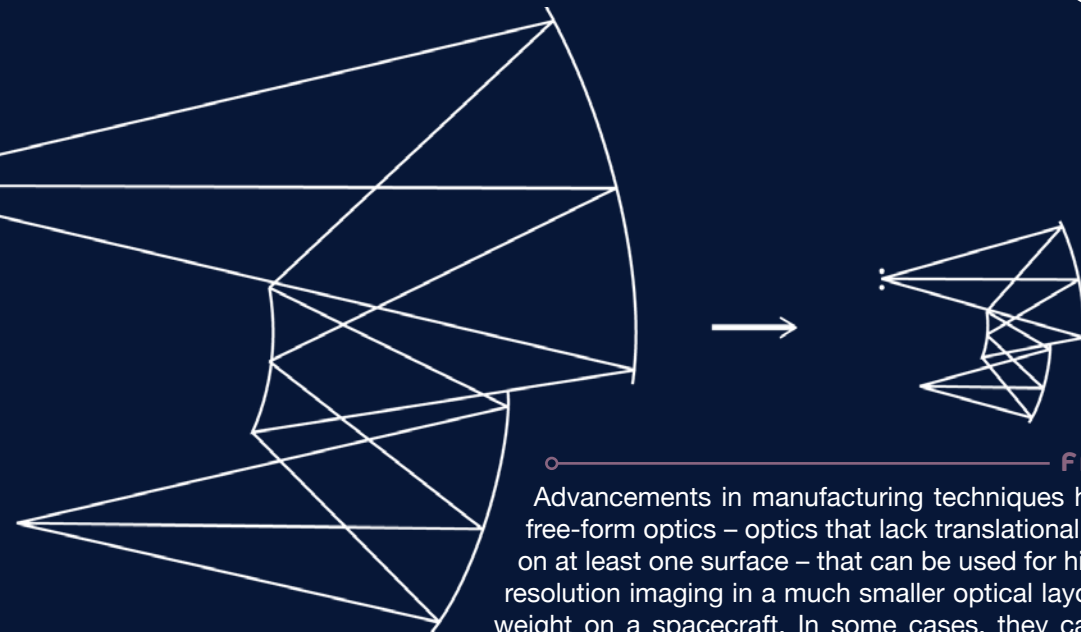
Metamaterials/ Metasurfaces

These engineered nanostructured materials can respond to light in entirely new ways – hyperlensing, negative refraction index, complex filtering, light channeling, etc – and have the potential to greatly reduce the size and mass of optical systems. Low profile metasurface antennas are also under development that are capable of beam shaping, pointing, and simple on-surface control of the aperture fields.

Distributed Observing System Design

Future missions will take advantage of autonomy, on-demand tasking, and dynamic reconfigurability to make entirely new measurements and observations. From early in the planning stage, these kinds of multi-platform, distributed observations require careful mission design, estimation of science value, and coupling of data products.

Free-form Optics

Advancements in manufacturing techniques have enabled precision free-form optics – optics that lack translational or rotational symmetry on at least one surface – that can be used for high spectral and spatial resolution imaging in a much smaller optical layout, saving volume and weight on a spacecraft. In some cases, they can even provide better overall imaging performance for high aspect ratio applications.

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